ENERGY CONSERVATION EXPERIENCES WITH HVAC SYSTEMS IN THE HIGH HUMIDITY CLIMATE, A CASE HISTORY

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The purpose of this paper is to discuss several commonly encountered problems associated with attempts to air condition buildings in the humid environment. It, first, reports observations made in the course of studying the air conditioning systems in approximately one hundred buildings at USMC Camp Smedley D. Butler in Okinawa, Japan. Three common problems are then discussed in some detail.

It was found that in many cases humidity considerations lead to situations which were energy wasteful. In many instances this could be attributed to either design or operational errors. The most common error found was the selection of an improper method of capacity control. Methods of improved capacity control are suggested and the need for additional work is pointed out.

INTRODUCTION

During the summers of 1983 and 1984 Engineering Sciences, Inc. personnel performed field surveys of approximately one hundred buildings at USMC Camp Smedley D. Butler in Okinawa, Japan under a contract with the Pacific Division of the Naval Facilities Engineering Command. The purpose of this contract was to identify deficiencies in the air conditioning equipment which affects its energy consumption and its ability to provide the required space conditions.

The first step in this process was to perform a rather extensive field test of the air conditioning equipment and its controls. The ESI field survey team measured all pertinent operating variables (e.g., air flows, dry and wet bulb air temperatures, air static pressures, water flows, water/refrigerant temperatures, water pressure drops, all appropriate motor electrical data, etc.). All control equipment was exercised over its entire range of motion and readings retaken for all variables. In addition dry and wet bulb air temperatures were taken throughout the conditioned spaces and a thorough visual inspection made of the equipment and the spaces that it served. More specifically, sufficient engineering data was collected to allow the calculation of thermal loads for the buildings.

Using the data collected the operating point for each piece of equipment was identified and used to specify the operating point of the entire air conditioning system at the time of the survey. From knowledge of the ambient conditions and loading at the time of the survey, it was possible to predict the performance of the equipment at design conditions and at the various part load conditions that it will experience during the course of a year. (This was possible through the use of a number of computer routines that ESI has developed for this purpose.)

Having analyzed the systems in this fashion, deficiencies (in design and/or condition) which cause them to fail to perform their desired function in an efficient manner could be identified. Recommendations were then made to correct these problems and supporting calculations performed to assess the economic attractiveness of each investment.

As expected, many of the problems observed in the course of the work were humidity related. This is consistent with the fact that Okinawa is a very humid environment. Ambient design conditions (2.5 %) are 88/80 (°F/°F). As a result coils will frequently see loads which are at least half latent. Under these conditions everything must be close to perfect to avoid humidity related problems. Unfortunately the opportunity existed to observe numerous such problems.

Although there are many different types of humidity problems that can occur, those most commonly found in Okinawa were:

1. Condensation during normal system operation. It was frequently found that moisture in the room air would condense on cold surfaces around supply air diffusers during normal operation of the system. Direct evidence of this was simply the presence of moisture on these surfaces at the time of inspection. Indirect evidence included a number of cases where the diffusers and surrounding ceiling material was discolored and corroded. Occupants in these spaces reported that, at times, it literally "rained" from the supply air diffusers. Poor comfort conditions and significant property damage were common.

2. Condensation on walls, floors, etc. at the time of shutdown of equipment. In several cases it was found that moisture from the room air would condense on walls and floors when the occupants attempted to shut the equipment off during an unoccupied period. This problem was less common but very serious in that the response had been to discontinue shutdown and operate the equipment without regard to occupancy. The obvious result was a great energy waste.

3. Condensation on diffusers at the time of startup after shutdown. It was frequently reported that unoccupied shutdown had been discontinued because, upon restarting, moisture would

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condense on the diffusers and cause property damage. This condition was verified by the field team. Again the result was that shutdown was forfeited and the equipment operated continuously without regard to occupancy. As before, this caused considerable waste of energy.

This paper will concentrate exclusively on these three issues. Primary attention will be given to the problems associated with condensation during normal operation (No. 1). No. 2 and No. 3 will be discussed in general terms and recommendations made. This is not meant to minimize the myriad of other humidity related issues which affect buildings in these climates. The field is well developed and much has been written.

It should also be pointed out that there are a number of design issues which can tend to increase the severity of the above three problems. These will be mentioned only briefly:

1. Chilled water temperatures are frequently found to be elevated for the sake of energy conservation. In addition to being a poor way of saving energy, this will usually result in a loss of latent capacity and a loss of humidity control in the space. (Figure 1 shows the effect of entering chilled water temperature on the sensible and latent capacities of a typical coil.) Chilled water temperatures in humid climates should be kept as low as possible.

2. Ventilation air brought in through the air handling unit is often reduced to save energy. Unfortunately this is usually done without a corresponding reduction in exhaust air. As a result pressurization is lost and infiltration is increased. In a humid climate this is particularly bad because the infiltrating air brings a high moisture load directly into the conditioned space, raising the room dew point. (Figure 2 shows the change in room condition due to the exchange of ventilation air for an equivalent amount of infiltration.) All spaces should be pressurized with conditioned outside air.

3. Most of the buildings inspected were very "loose" and experienced a high rate of infiltration. In some cases there was even a design tendency to encourage "fresh air". (Figure 3 shows the equilibrium room conditions for various amounts of infiltration.) Every effort should be made to make the spaces as tight as possible to minimize the amount of moisture brought directly into the space.

4. In many cases it was found that cooling coils had not been selected with proper care. Most often this meant that the coil was selected without consideration of likely part load conditions. All coils should be checked for performance under the entire range of conditions they may be subjected to.

CONDENSATION ON DIFFUSERS DURING NORMAL OPERATION

Nature of the Problem

Probably the most common problem observed in Okinawa was the condensation of moisture on supply air diffusers. Figure 4 shows a typical ceiling diffuser. Condensation occurs when warm, moist air comes into contact with a solid object having a surface temperature below its dew point.

This can occur in several ways. The first possiblity concerns modulating type control systems. With these systems one does not normally see a sudden change in the condition of the supply air being discharged at the diffuser. In this case the primary mechanism for condensation is the induction of room air. Moist room air is induced to flow along the ceiling and over the outer casing of the diffuser. The ceiling and diffuser casing are cooled by both conduction and the effect of air leaked at the connector.

As one might imagine, this is a very geometry specific phenomenon. It is a well known fact that in most cases one can supply air at some temperature below the room dew point without condensation occurring. But, to our knowledge, no one has experimentally or analytically quantified the allowable temperature depression. (Somewhere in the range of 5°F to 7°F is generally felt to be acceptable. This has, indeed, been confirmed by ESI's observations in Okinawa.)

There does seem to be a marked difference in the tendency of different diffuser designs to experience condensation problems when subjected to the same supply air/dew point depression. Again, to our knowledge, no one has succeeded either experimentally or analytically in giving more than qualitative guides for selection of diffusers for this type of service. It is generally agreed that the smaller the outer casing (to act as a fin) and the lower the air velocity (to induce a room air flow) the better. Some have suggested that plastic diffusers would be worse conductors and, hence, better. The validity of the outer casing factor was verified by the field work in Okinawa. The types of diffusers which seemed to be most susceptible to this problem had large metal outer rings surrounding them.

In many cases where problems were observed the cause was found to be air leaks in the flexible connector. This seems to be of critical importance in these climates. (The separate, but related problem, of moisture condensation inside duct insulation was also commonly found and frequently associated with air leakage.)

Method of Capacity Control

By far the most important factor influencing the formation of condensation was found to be the method of capacity control employed. One control which was frequently found on smaller DX systems was to close a refrigerant solenoid in response to satisfaction of a room or return air thermostat.

Generally the air handling unit fan was allowed to run continuously. Much has been written of the effects of reevaporation on room humidity ratio in control systems of this type (1). An additional problem can be seen when one considers that the air handling unit begins to send an unconditioned mixture of returned room air and outside ventilation air through ducts and across diffusers which were, moments before, cooled by cold supply air. Observations of ceiling stains and rusted diffusers reinforced the cases where actual condensation formation of this type was observed. Speilvogel confirms these observations in an earlier study also performed for the Navy (2).

The impact of the method of capacity control on condensation is somewhat more subtle for modulating types of control. It can be reduced to the following two issues: 1) How well is the room humidity controlled? 2) How does supply air dry bulb temperature vary with load? The first issue will dictate the room air's dew point and the second determines the temperature depression as a function of load.

All methods of modulating capacity control can be thought of as variations of two basic methods. The first is to decrease the amount of water allowed to flow through the coil. This causes the effective temperature of the coil to rise and hence less heat transfer occurs. The second is to decrease the amount of air flowing through the coil. This also reduces the amount of heat transfer. (Actually there is a third possibility. One could vary the temperature of the water entering the coil but, as has already been shown, this has undesirable consequences and is not generally found.)

Before discussing each of these, some consideration should be given to likely part load conditions. It has been generally found that the coil sensible heat ratio required for most common part load conditions is lower than that required at design conditions. This tendency is particularly true in humid climates such as Okinawa.

Consider a case which was found to be problem prone. Mess halls typically have large internal loads due to people and food service. Suppose that an air conditioning system has been designed to satisfy the load when the ambient is 88/80 (°F/°F). There will, of course, be a solar load included in the design calculations. A part load condition frequently encountered is that of a rainy day during the design month. Observation has shown that the ambient humidity ratio remains relatively constant throughout any given day. (The relative humidity is inversely related to the dry bulb temperature.) On a rainy day the ambient dry bulb might go to 80 °F but the wet bulb might well be as high as 78 °F. The latent load due to ventilation and infiltration air is unchanged but the sensible load has been reduced 80%. The solar load (all sensible) is reduced to zero. The internal people and food service load is unchanged. The net result of all of this is that the sensible heat ratio required of the coil is diminished substantially. This is, admittedly, an extreme case but the same general tendency is seen in a variety of building types.

A computer program has been developed which is useful in predicting the performance of a given coil under various loading conditions. This program is based upon principles described by Nussbaum but uses known performance at one set of conditions to determine empirically those constants which determine its performance at other conditions (3). In this manner one can input one known operating point and predict how the coil will behave under any other set of circumstances. This program has been used extensively in the following manner.

Figure 5 shows the performance of a typical chilled water coil through which the water flow is varied. The plot shows that the latent capacity falls off much faster than the sensible capacity. This is just the opposite of what is desired and the result will be that the room humidity and dew point will increase at part load conditions. The temperature of the supply air increases as the capacity decreases. This is a very desirable characteristic in trying to avoid condensation.

Figure 6 presents the same information for the case where the air flow is varied. The coil is uncontrolled in this case. One can see that the sensible capacity falls faster than the latent resulting in a lower sensible heat ratio at part loads. This is as one would want. But notice that the supply air temperature falls very rapidly as the load is decreased. If the room dew point were to remain relatively constant at 63 °F (78 °F with relative humidity of 60% as Navy design criteria requires) the depression of the temperature of the supply air below dew point would increase rapidly and condensation would be experienced. (One might attempt to solve this deficiency by controlling the supply air discharge temperature with a valve on the chilled water line but it can be shown that this immediately begins to display the sensible heat ratio increase found with the chilled water valve method discussed above.)

Figure 7 shows what is commonly referred to as face and bypass control. This is, however, nothing more than variable air flow through the coil in which the air not put through the coil is bypassed and mixed back with that which has been cooled and dehumidified. In fact, the heat transfer is exactly the same as the case discussed for variable air flow. The sensible heat ratio falls in the same way that it did (and as is desired). The supply air temperature, however, rises quickly as the load is reduced. This solves the problem of increasing depression and avoids the potential for condensation problems found with the variable air flow system.

As can be seen the supply air temperature for the face and bypass system rises much faster than is necessary. This suggests the possibility of combining the face and bypass with the variable air volume system (Figure 8). The fan speed might be modulated by a variable frequency drive which is controlled by a room thermostat. The face and bypass dampers could then be controlled to achieve a fixed discharge air temperature. This would make it possible to achieve the fan savings available with a variable air volume system without the objectionable drop in discharge air temperature and with the falling sensible heat ratio characteristic of the face and bypass system. Although seeming to hold promise, this system has not yet been investigated in depth.

From these plots the impact of oversizing chilled water systems can be clearly seen. Where a chilled water valve or variable air volume system has been used, the system will always be operating at low part loads and will tend to experience either loss of humidity control or condensation problems.

Figures 9 and 10 summarize the information for the three control methods discussed. One can see from Figure 9 that the chilled water valve control should be eliminated because of its sensible heat ratio characteristic and from Figure 10 one can see that the variable air flow should be eliminated because of its supply air temperature characteristic. Only the face and bypass remains as a viable method of modulating control under extremes of humidity.

The next step is to look at the dynamic interaction of the room loads with the coil and its method of capacity control. The same coil model described earlier has been incorporated in a room simulation program to do this. The chilled water valve program, for instance, adjusts the water flow through the coil in response to the room dry bulb temperature (assuming linear porportional control) until the sensible cooling being done by the coil is balanced by the loads on the space. It then outputs all of the pertinent data (e.g., dry/wet bulb temps for room and supply air as well as room and coil loads, etc.).

Figures 11 and 12 show the equilibrium room conditions which would be reached for a typical building at some commonly found part load conditions for the chilled water valve and face and bypass control systems respectively. As can be seen, the room is slightly outside the ASHRAE comfort region at design conditions. This results from a slight oversizing of the coil. (One should note that the Navy design criteria of 78 °F and 60% relative humidity controlled by a thermostat set at 78 °F and a 4 °F throttling range will, in fact, give conditions slightly outside the comfort zone.)

The 80/78 (°F/°F) ambient is seen to be a problem for both methods of control. The room relative humidity has drifted up and the dewpoints are 68.2 °F and 66.5 °F respectively. The 75/69 and 70/65 (°F/°F) ambients are typical for spring and fall in Okinawa. As can be seen the face and bypass system can serve both of these loads well but the chilled water valve still cannot maintain humidity control. The final data point represents what was commonly found to be the occupant's response to an uncomfortable condition (i.e., lowering the thermostat to 72 °F). Both systems give room conditions within the comfort zone. The lower room temperature has resulted in an increase in coil load of approximately 18%. All of these findings are consistent with what was observed in the buildings in Okinawa. The results were frequently masked by the fact that the chilled water temperature had been raised from 45 °F to 55 °F. As seen here, the occupants would then generally lower the room thermostat to 68 °F or 70 °F. As a result little or no compressor energy would actually be saved. The variable air flow control system has been excluded because it gives supply air temperatures 10 to 20 °F below the room dew points and is, hence, unacceptable.

Larger DX systems are normally found to have a solenoid valve on the refrigerant line controlled by a room (or return air) thermostat. There will frequently be a horizontally split coil with two solenoids controlled by a two stage thermostat. The fan is almost always run continuously. As mentioned earlier, these systems give rather poor humidity control due to reevaporation and are prone to condense on the diffusers during the off cycle. If one were to plot room humidity versus time it would be found to climb upward during the off cycle and be brought back down during the on cycle. Field measurements have shown that it will remain unacceptably high throughout both periods. This method of control is not recommended for high humidity environments.

Control Recommendations

The method of capacity control which was recommended for most systems in Okinawa was on/off fan control. The existing systems were generally either chilled water or refrigerant solenoid valves controlled by room thermostats. All fans run continuously. Figures 13 and 14 show simple schematics for chilled water and DX respectively. For chilled water the recommendation is that the coil be allowed to run wild (chilled water valve fixed in the fully open position) and the air handling unit fan cycled on and off by the room thermostat. The DX unit could continue to close the solenoid valve but would also shut the fan off during the off cycle. In this way the coils would operate at full capacity whenever they are in the on cycle and, hence, will build to full latent capacity under all loads. Khattar, Ramanan and Swami have shown that for DX systems experiencing 25% compressor run time, the cycled fan will deliver 2.5 times as much latent cooling as the continuously running fan (1). The competing options were forms of modulating control (i.e., the combination of variable air volume and face and bypass which has been discussed). This would have required changing out the air handling units. The incremental investment could not be justified.

These methods of control have some major benefits but also have some severe limitations that must be addressed. On the benefit side, they achieve fan savings which would not otherwise be possible. This was found to be of major importance in most of the Okinawa buildings. Another benefit is achieved due to the fact that outside air is brought in only intermittently. With many of the buildings having high (but variable) internal people loads, the effect is to run more when the people are present and, hence, bring in more outside air precisely when it is needed. (As mentioned earlier, care must be taken not to negatively pressurize the space. This might require that associated exhaust fans be cycled with the air handling unit fan.) The combined effect of these two items in many cases amounted to a very significant energy savings over the existing method of control while at the same time improving comfort conditions in the space.

By no means are these recommendations appropriate for all types of spaces. They were appropriate in Okinawa because of a combination of circumstances which may, or may not, be commonly found. First, if intermittent ventilation is not acceptable some other means of control should be found. It should be pointed out that the existing continuous operation of the fans on DX units is not acceptable in humid climates due to the condensation problems commonly observed. (Therefore it might have otherwise been necessary to go to some form of modulating control. This would have involved a major investment in new air handling and possibly refrigeration equipment.) Secondly, the space should not be subjected to extended periods of extremely light loads. Under these conditions the coils (and fans) will cycle too often and proper dehumidification will not be achieved. In Okinawa high ambient air enthalpies and loose buildings combined to provide relatively high loads a large fraction of the time. Finally, noise from belts and expanding/contracting ductwork might also be objectionable in many types of spaces. In Okinawa this was not the case.

In addition to these design considerations there are a number of equipment concerns which might be legitimately raised. It is common knowledge that starting and stopping a motor will decrease its expected life. NEMA has recently published guides for duty cycling limitations on motors of various sizes and duties (4). The number of starts and stops that might be expected with these methods of control appear to be within the acceptable limits for all of the cases examined. Fortunately it is found that the total time required for the system to pull the room temperature down plus the time required for the room to float back up to the cut-on point is relatively constant and insensitive to load. It is also worth noting that the present worth of expected savings would greatly outweigh any reasonable assumptions as to costs for premature motor failure. While less definitive information exists for the effect on belt and pulley life, the cost of replacement for these items insure that the savings will again overwhelm any reasonable values that one might assume. The first year savings for a typical 10 hp motor in Okinawa (with $0.10/kwh electricity) is approximately $1000/year. The present worth of this is on the order of $14,000 while the replacement cost for a 10 hp motor might be approximately $400.

In the event that the space in question is such that fan cycling is not possible, some form of modulating control will be required. Only those methods having at their base a face and bypass concept (e.g., multizone, dual duct, etc.) will deliver the right type of sensible heat ratio and supply air temperature at part load conditions. The combination variable air volume and face and bypass described earlier and shown in Figure 8 seems to merit further investigation and might be a way to achieve the fan savings of VAV while meeting the particular requirements of the high humidity environment.

PROBLEMS ASSOCIATED WITH SYSTEM SHUTDOWN

When the equipment conditioning a space is shut down there is the potential for moisture to condense on walls, floors and other surfaces in the space. When the equipment is turned off, the dew point in the space immediately begins to rise. At the same time the surface temperature of all objects in the space begins to rise and will tend to follow the room dry bulb. The question is simply whether the dew point will increase enough faster to get significantly ahead of the surface temperatures. If it does, condensation will occur. This phenonomon was reported but not observed in Okinawa. (It was, however, actually observed in the course of a similar project in Jacksonville, Florida.)

Figure 15 shows the increase of room dew point if one assumes a simple no capacitance dilution mass balance on the room's moisture content. The room is assumed to start at 78 °F and 60% relative humidity and the infiltrating ambient air is assumed to remain constant at a typical Okinawa August 5 P.M. value. In fact, the room dew point will not increase this fast. Kusuda and Miki have accounted for the capacitance and moisture absorption/release rates of room furnishings in a typical residence and have shown that the effect can bear significantly on the room's dew point (5).

The question of surface temperature is even more complicated. Most room finishes and furnishings are composite materials. The problem is to predict the surface temperature as the room dry bulb increases. This can be quite difficult. (The author has not attempted to deal with this quantitatively.)

Some general qualitative comments can, however, be made:

1. By keeping the room dry bulb as high as possible the surface temperatures of objects in the room can be started at a safe value. The ambient dew point at 5 P.M. on an August day in Okinawa is not likely to exceed 76 °F. If the room temperature is maintained at 78 °F no problems can occur. (The case which was observed in Jacksonville was one where the chilled water temperature had been raised and the occupants had

responded to their discomfort by maintaining 68 °F to 70 °F in the space.)

2. Room interior finishes and furnishings should, to the extent possible, be chosen for low thermal capacitance and poor thermal conductivity. This will have the effect of insuring that surface temperature will rise rapidly as the room warms up. (Unfortunately one generally finds painted masonry walls and a concrete slab floor in Navy buildings. A good selection in an office building might be carpet on the floor with grass cloth or vinyl wall covering.)

3. Interior partition walls and floors are more susceptible to problems than exterior walls. Exterior walls are (and continue to be) warmed by transmission loads. Interior partitions are cooled on both sides and contain no stored heat.

4. As can be seen from Figure 15, the rate at which the dew point increases is strongly influenced by infiltration. This constitutes another reason for making the building as tight as possible.

PROBLEMS ASSOCIATED WITH STARTUP AFTER A PERIOD OF SHUTDOWN

During a period of shutdown the conditions of the air in the space will approach those of the ambient air. At the time of startup the air in the room will be similar to the ambient air sometime earlier. As suggested by Kusuda and Miki, the moisture storage properties of the materials in the space will tend to moderate any swings of humidity (5). For this reason the room dew point will not be as high as one might predict using a no capacitance model. (This even suggests the advantage of having a large moisture storage capability in the room's furnishings and interior finish, as with carpet and certain ceiling materials.) In Okinawa a typical startup room condition was found to be 80/77 (°F/°F). When this warm, moist air is put into a cold coil the resulting supply air will often be 15 °F to 25 °F below the room's dew point. As an example if 80/77 room air is put into the coil supply air will be discharged at 60.6/60.4. This is 15.4 °F below the dew point of 76° F. All of the discussion in Section II about induction of room air is applicable and there is an excellent chance that condensation will occcur around the supply air diffusers.

In Okinawa the response was to discontinue unoccupied shutdown. As a result a major savings opportunity was forfeited. Some method had to be found to overcome this problem.

The key to any solution is to raise the supply air temperature without giving away the coil's latent capacity. The earlier discussion of the various methods of capacity control suggests a possible solution to the problem. Only the face and bypass gave elevated supply air temperatures without increasing the sensible heat ratio. For the example stated, bypassing 50% of the air will give supply air conditions of 66.6/65.1 (°F/°F). The supply air has been brought to within 9.4 °F of the room's dew point while the sensible heat ratio has gone from 0.34 to 0.35. If 75% of the air is bypassed the supply air will be 71.8/69.6 (°F/°F) and the sensible heat ratio will be 0.37. The supply is within 4.2 °F of the room's dew point. By making this field adjustable one can balance recovery time against discharge air temperature to find a workable setting.

The recommendation for "soft startup" of chilled water systems was that face and bypass dampers be placed in some set position during the startup period. (Both the position and the time period are to be field adjustable.) With DX systems the recommendation is to install horizontally split coils with separate refrigeration circuits and hold one of the refrigerant line solenoid valves closed during the startup period. (The startup period can still be field adjustable but the split is, of course, fixed.) In many cases the air handling units already have split coils and only a control modification is required. In this fashion it will be possible for the Navy to begin realizing the benefits of unoccupied shutdown in Okinawa.

SUMMARY

Of the myriad of problems which can occur when one attempts to air condition buildings in a high humidity environment, this paper examines three:

1. Condensation on diffusers during normal operation.

2. Condensation on walls, floors and furnishings during shutdown.

3. Condensation on diffusers during startup after a shutdown period.

The information presented in the paper is the result of work conducted under a contract with the Naval Facilities Engineering Command in which the objective was to evaluate and make recommendations for improving the performance and energy efficiency of the air conditioning equipment serving approximately 100 of the largest buildings at USMC Camp Smedley D. Butler, Okinawa, Japan. Okinawa, having an extremely humid climate, offered the opportunity to observe first hand most of the problems associated with high humidity air conditioning.

The second of the three problems mentioned (condensation during shutdown) was not found to be a major problem in Okinawa. In general, it can be avoided if only minor precautions are taken.

With respect to the first problem mentioned (condensation during normal operation), it was found that some errors in design and operation were repeatedly observed. The results were consistently poor comfort conditions in the space and significant property damage in a number of instances. It was further discovered that no quantitative guidelines are available to assist the engineer in making some very important design decisions. In particular it was observed that most of the methods of capacity control normally used are inappropriate in the high humidity environment. More specifically most methods were found to fail in maintaining control of room humidity and/or experience condensation problems under the most likely part load conditions. Of the methods of modulating control usually encountered, only face and bypass dampers (with an uncontrolled coil) performed satisfactorily in both respects. Chilled water valve and variable air volume failed miserably.

The common practice of cycling DX coils with refrigerant line solenoid valves while allowing the fan to run continuously was found to fail in both respects.

Where conditions would permit, it was suggested that both chilled water and DX units be controlled by fan cycling. In the chilled water case the coil remains fully activated and the air handling unit fan is cycled on and off by the room thermostat. In the DX case both the solenoid valve and the fan are cycled by the room thermostat. A significant savings in energy expense and an improvement in room comfort conditions will result from the implementation of these recommendations.

The final problem mentioned (condensation at startup after shutdown) was also found to be of major significance in Okinawa. In many cases shutdown of equipment during unoccupied periods had been discontinued because the occupants had experienced condensation at the time of startup. Control strategies were developed to allow a "soft startup" of the equipment and reduce the chance of moisture problems. Through this, shutdown will again become possible in Okinawa.

Reports have been submitted to the Navy on the work described in this paper. When funded the recommendations of this study will produce an annual savings of approximately $2.1 million/year with an investment of approximately $4.8 million. The bulk of these savings is the result of the two items which are the primary concern of this paper; improved capacity control and shutdown during unoccupied periods.

There are many questions raised by the work of this contract. Some of the more important items requiring further investigation include:

1. Analytical and experimental work needs to be done with regard to the induction of room air in the vicinity of a supply air diffuser with emphasis on the tendency for condensation on cool surrounding surfaces.

2. Improved methods of modulating capacity control should be investigated. The combined face & bypass and variable air volume system discussed is an example of the types of systems which might offer both energy economy and proper humidity control.

3. The issue of soft startup strategies requires considerable additional investigation.

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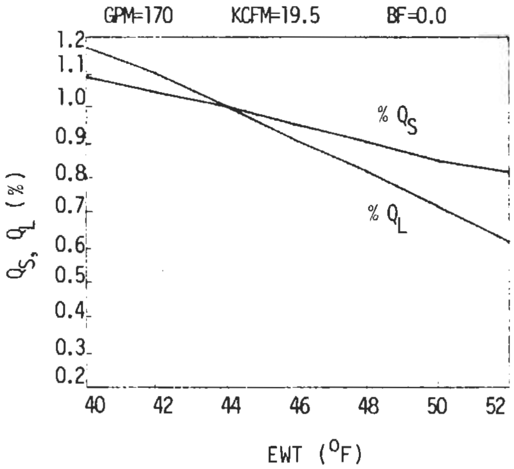
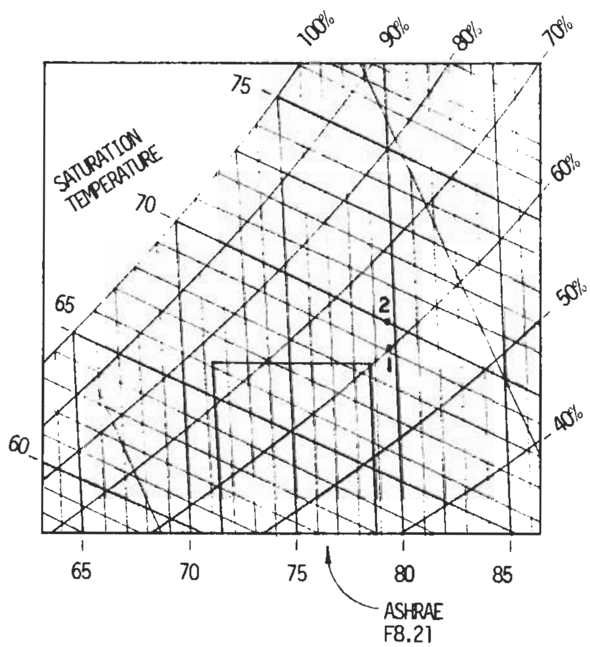


FIGURE 1

EFFECT OF ENTERING WATER TEMPERATURE

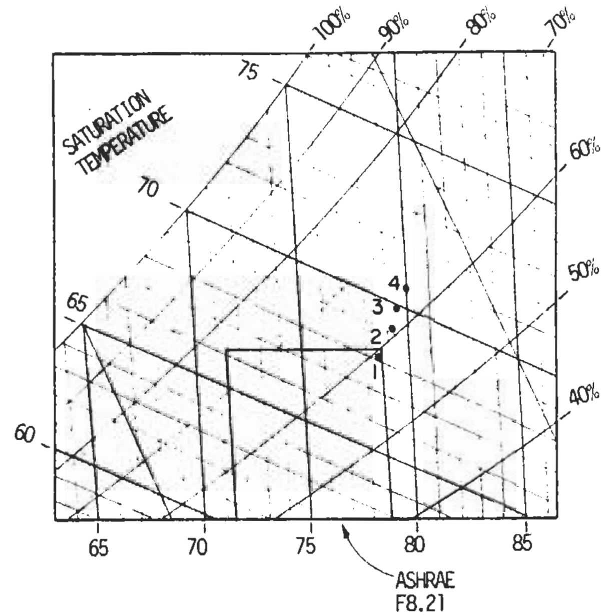


1: V = 2500 CFM
I = 4000 CFM

2: V = 0
I = 6500 CFM

FIGURE 2

EFFECT OF SWAPPING VENTILATION & INFILTRATION



1: 2000 CFM
2: 4000 CFM
3: 6000 CFM
4: 8000 CFM

FIGURE 3

EFFECT OF INFILTRATION ON ROOM CONDITIONS

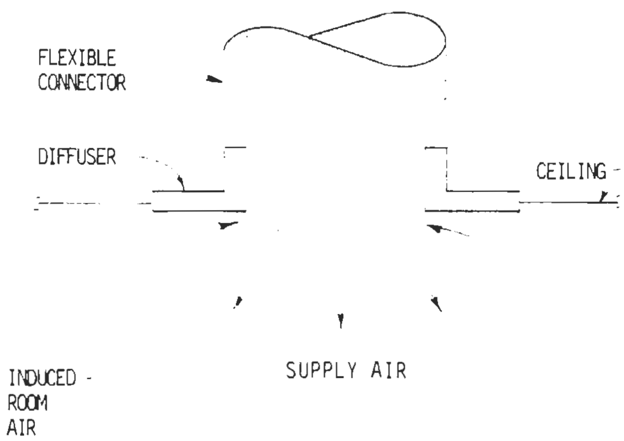


FIGURE 4

TYPICAL CEILING DIFFUSER

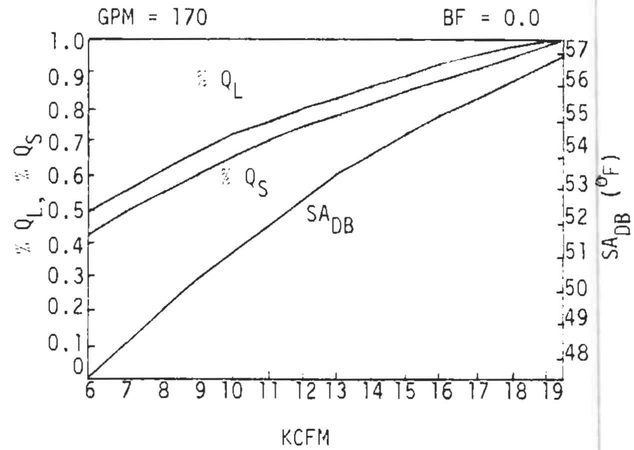


FIGURE 6

EFFECT OF AIR FLOW

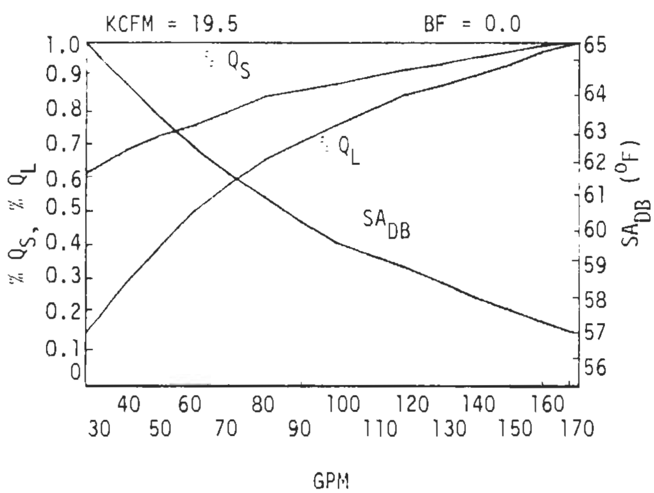


FIGURE 5

EFFECT OF WATER FLOW

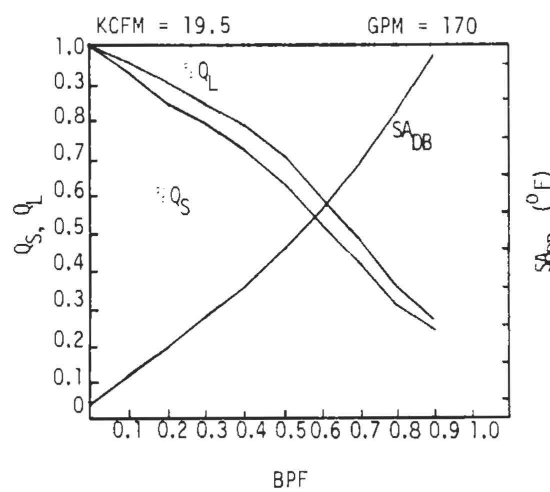


FIGURE 7

EFFECT OF BYPASSING

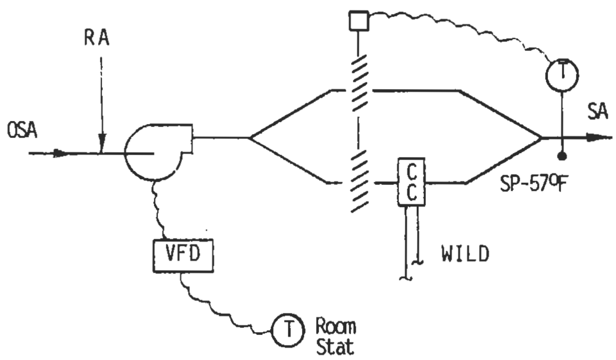


FIGURE 8

COMBINED F/B & VAV SYSTEM

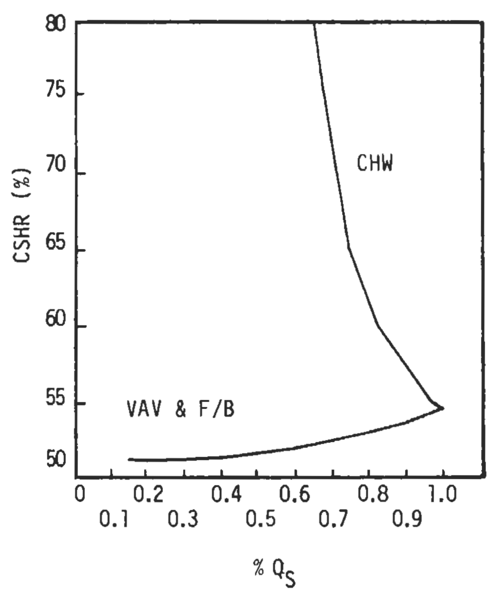


FIGURE 9

COIL SENSIBLE HEAT RATIO

VS. % SENSIBLE COOLING CAPACITY

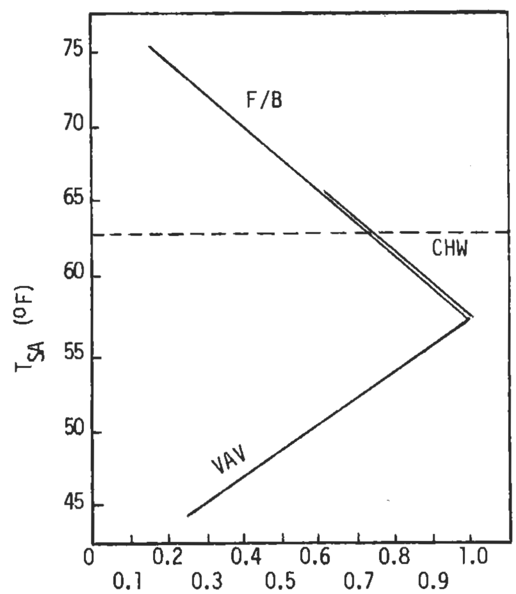
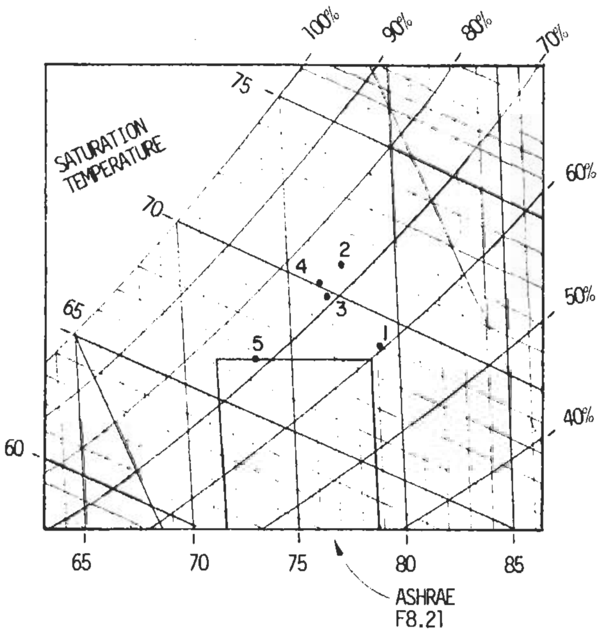


FIGURE 10

SUPPLY AIR DRY BULB TEMPERATURE

VS. % SENSIBLE COOLING CAPACITY



CHW VALVE CONTROL

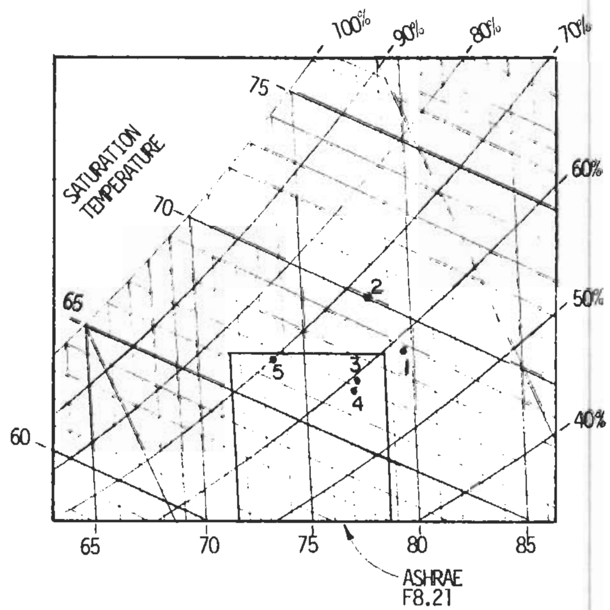
CONDITIONS

1. DESIGN DAY
2. TROUBLE PLC WITH 80/78
3. TROUBLE PLC WITH 75/69
4. TROUBLE PLC WITH 70/65
5. TROUBLE PLC WITH 80/78
   TSTAT=72° F

NOTE: Q_T, #2 = 632.8 KBTUH
Q_T, #5 = 750.9 KBTUH

FIGURE 11

CHW VALVE UNDER VARIOUS LOADS



F/B DAMPER CONTROL

CONDITIONS

1. DESIGN DAY
2. TROUBLE PLC WITH 80/78
3. TROUBLE PLC WITH 75/69
4. TROUBLE PLC WITH 70/65
5. TROUBLE PLC WITH 80/78,
   TSTAT =72° F

NOTE: Q_T, #2 = 648.4 KBTUH
Q_T, #5 = 750.2 KBTUH

FIGURE 12

F/B CONTROL UNDER VARIOUS LOADS

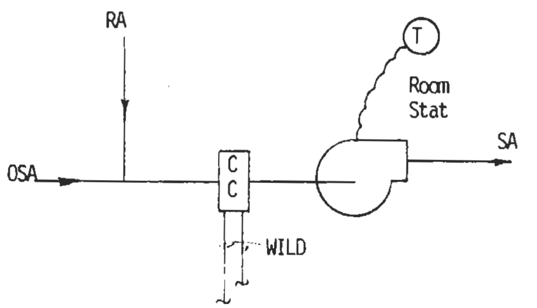


FIGURE 13

FAN CONTROL - CHILLED WATER COIL

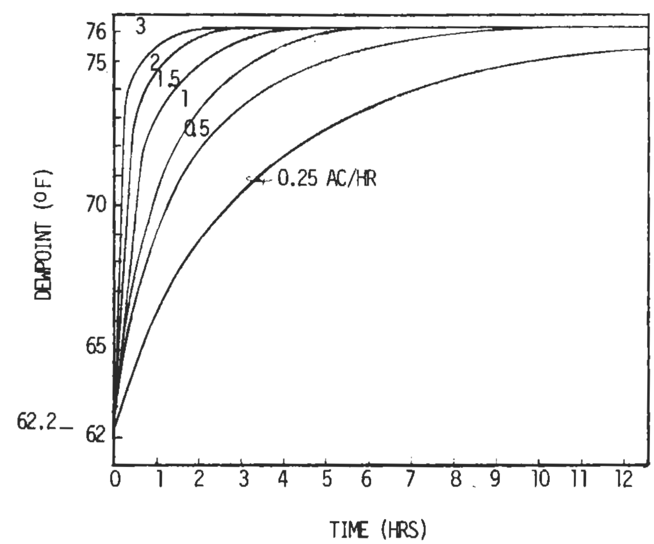


FIGURE 15

ROOM DEWPOINT VS. TIME AT SHUTDOWN

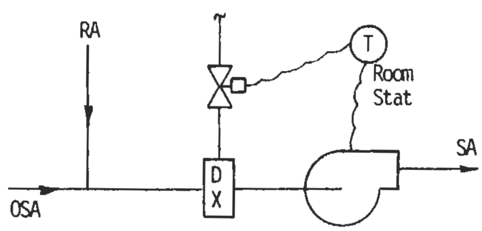


FIGURE 14

FAN CONTROL - DX COIL